Introduction

The following paper will address the liquid hydrogen (LH2) logistics technology used by NASA for aerospace programs, and draw some interesting links between NASA and commercialization of hydrogen.

LH2 Logistics Technology for NASA

The KSC is the LH2 purchasing agent for NASA who has responsibility for the procurement of LH2 to satisfy all requirements of NASA and its contractors according to Federal Acquisition Regulation (FAR) 18-8.002-73. The LH2 is procured under Military Specification MIL-P-27201, which specifies minimums of 99.995% purity and 95% para-hydrogen.

<u>Suppliers</u>
The two current suppliers of LH2 to NASA are Air Products and Chemicals, Incorporated; and Praxair, Incorporated. NASA has 4 LH2 contracts which have a combined contract value greater than $300 million.

<u>Users</u>
There are fourteen routine NASA delivery locations across the country with a total annual consumption of fifteen to eighteen million pounds. NASA has purchased more than three hundred million pounds of LH2 over the last forty years. Many millions of miles of over the road LH2 transportation have occurred safely and without a hydrogen incident.

<u>Transportation</u>
Unfortunately, except for Stennis Space Center (SSC), most users are located hundreds of miles from the suppliers. KSC is 800 miles from the Air Products plant is New Orleans, La. This separation of user/supplier makes transportation an important issue in the cost of LH2. For example, the cost of transportation of LH2 to KSC accounts for 31 % of the delivered LH2 cost. Other than cost, another transportation consideration is scheduling. Large quantity requirements in short time periods put a strain on industry's

truck transportation fleet and the user operations must be scheduled accordingly to limit the high cost of peak usage and the associated idle periods between peaks. This is especially important to KSC where rapid replenishment of the large 850,000-gallon capacity storage tank is essential to support frequent test and launch rates.

The most familiar form of LH2 transportation is the truck tanker. It offers the greatest flexibility, but is also the lowest volume and most expensive mode of LH2 transportation. Recent increases in tanker volumes have improved efficiencies somewhat, but highway size restrictions limit optimization.

The railway tank car offers increased volume but reduced flexibility due to limited rail systems. NASA has four LH2 railcars and there are about twenty in the industry. NASA/KSC performed successful demonstration runs to test operational and economic feasibility, but rail deliveries were discontinued due to unacceptable delivery times and rail system inefficiencies.

The waterway barge offers the largest capacity, but the least flexibility. It is ideal for applications such as SSC where there is a relatively short distance between origin and destination points, and large volumes of LH2 are required. Waterway access and weather are obvious limitations.

Ideally, the LH2 supplier and large user would have all three modes of LH2 transportation available. This situation allows choice of transportation system based on the most economical and timely delivery method for the specific requirements of volumes, schedules, and operational applications.

Government LH2 Storage Capacity

LH2 storage capacity at major Government user locations totals 5,575,000 gallons. The majority of Government LH2 storage is located in the southeastern United States with the largest storage volume located at KSC in Florida. There is approximately 1,800,000 gallons of inactive LH2 storage capacity in California, primarily at Vandenberg AFB and Santa Susana Field Laboratory.

Shuttle LH2 Storage Systems

There are four different LH2 storage vessels that are typical of current technology.

*Tanker Trucks - Surprisingly, the LH2 tanker trucks may reflect the most advanced, high efficiency thermal insulation technology. Modern LH2 tanker trucks utilize good vacuum jacket technology with multi-layer insulation. These vessels are constructed of stainless steel inner tanks and carbon steel outer tanks with capacities of up to 17,500 gallons. Normal evaporation rate (NER) is the common thermal performance criteria rating and modern containers can achieve less than 0.2% per day. Another rating criteria is Hold Time. Hold Time may be as high as forty-five days for this type of container, when configured as an ISO shipping container. Modern LH2 trailers have typical one-way travel times of more than 50 hours without venting, which is sufficient for cross-country delivery.

* Pad Storage Tanks - LH2 is off-loaded into the 850,000 gallon storage tank via vacuum jacketed transfer lines. Although this storage tank is over forty years old, it is typical of the current large tank insulation systems. The vacuum jacket is filled with perlite insulation. NER of 0.1% to 1 % per day is typical.

* Shuttle External Tank - The external tank on the Shuttle has on board capacity of 384,000 gallons, although the loading operation consumes 460,000 gallons. Approximately 100,000 gallons are lost to vaporization each time the LH2 flows from the pad storage tank to the Shuttle external tank, or the reverse, in the case of a launch scrub. The external tank insulation system consists of polyurethane foam sprayed onto the outside of the aluminum skin and is the least thermal efficient insulation system, but simple and lightweight.

* Shuttle Fuel Cell Tanks - The most complex of the Shuttle LH2 storage tanks are the Power Reactant Storage and Distribution Systems tanks, more commonly known as fuel cell tanks. One liquid oxygen and one LH2 tank are grouped as a set, and five sets are typically used for flight. Each LH2 tank is constructed of aluminum and can store 155 gallons. These tanks are vacuum jacketed with a radiant heat shield in the vacuum space. A vacuum ion pump maintains the vacuum level. There are built-in heater elements to vaporize the LH2 to maintain sufficient pressure to feed the system. These

tanks must be robust enough to survive the forces and vibrations of launch.

Vehicle launch and landing processing is KSC's primary mission. Therefore, our research projects and studies are usually concerned with improvements in launch operations, safety, facility improvements, and cost reduction. Cost reductions for LH2 operations at KSC are aimed at improved production, distribution, storage, and transfers. Considering the limited number of LH2 production locations, and the significant distance to most user locations, hydrogen transportation and storage are very important to the aerospace customers.

Logistics of hydrogen production, transportation, and storage may be even more challenging to meet the hydrogen demands of ground transportation vehicles and power generation units because there is a more diverse customer base and requirements are not localized. However, based on the experience of aerospace hydrogen customers, the current hydrogen supply industry in the United States is capable of supporting the requirements of a developing hydrogen economy and can expand their supply capabilities to meet the hydrogen demands in the foreseeable future.

Links between the Federal Government (NASA) and Hydrogen Commercialization

Congratulations to the Department of Energy, especially Energy Efficiency and Renewable Energy (EERE), for their timeless efforts to establish a hydrogen based energy economy in the United States. Their policies and funding make it possible for our National Labs, universities, and commercial sector to join together to accelerate hydrogen related knowledge and to develop products that may not happen otherwise.

We have all complained about the Federal Government in one way of another, but the fact is that government programs are usually needed to initiate, or accelerate, programs that have significant societal benefits, but initially are not economical. As Energy Secretary Abraham said recently, “the Federal Government takes necessary steps to smooth the economic transition”. Just as government mail hauling contracts supported the struggling early airplane industry, and the Helium Conservation Project encouraged development of an infant industrial gas industry, the benefactors of DOE's hydrogen and fuel cell program will grow from the laboratories to the public.

Early DOD and NASA unique requirements helped establish and nurture today's hydrogen industry. The first liquid hydrogen production plants resulted from government contracts to design, develop, and build a hydrogen logistics system to support a classified project called Suntan in the 1950's. The goal of Suntan was to fly airplanes using hydrogen fueled jet engines. A half-century later we need that capability more than ever. Imagine the military advantages of eliminating the gigantic logistics burden of supplying jet fuel to aircraft carriers if the aircraft were fueled with hydrogen made on-board the carrier from waste heat and sea water. Imagine the impact of reduced petroleum consumption and reduced are pollution if commercial airlines were fueled with hydrogen. The bad news is that hydrogen fueled jet engines only reached the demonstration stage as a result of the Suntan project; the good news is that the development of liquid hydrogen production, storage, and distribution technologies were the beginning of today's hydrogen industry. Government contracts for large scale liquid hydrogen production plants to supply early DOD and NASA aerospace programs enabled industry to grow a significant hydrogen business which expanded to the commercial sector.

Fuel cells have been known to science for more than 150 years. It took unique requirements by NASA's Apollo program to provide the incentive to develop and produce the fuel cell as it is generally recognized today. Although expensive, the fuel cell was the solution to the government's unique requirements for aerospace applications. Fuel cell costs are still a hurdle today for large scale commercialization, but government and commercial efforts to increase applications and reduce costs will smooth the economic transition and increase acceptance by the public sector.

Although NASA usage of hydrogen has primarily been related to aerospace applications, many of the same challenges apply to ground applications, especially to the use of hydrogen in light weight vehicles. There is an interesting parallel between hydrogen use on the Shuttle (an aerospace transportation vehicle) and the BMW 745h sedan (a terrestrial transportation vehicle). Other than both being very expensive, hydrogen use in both vehicles is similar.

-hydrogen is stored on the vehicle as liquid hydrogen
-hydrogen combustion provides propulsion; rocket engines on the Shuttle and internal combustion engine on the BMW
-hydrogen fuel cells provide electrical power for auxiliary systems.
-hydrogen sensors and pressure controls are critical for safe operation.

A favorite photo of the Southeastern Region of the United States was taken from orbit through the window of a hydrogen powered government vehicle, the Shuttle. The photo shows water all around the coastline and many fresh water lakes. With this abundant source of hydrogen (pictured as water in the photo), the government, industry, and academia can work together to enable the public to take some photos of this beautiful region through the window of a hydrogen powered, commercially available, terrestrial vehicle.